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Strength of the thigh muscles, namely the hamstrings and quadriceps, is a strong determinant of athletic performance and recovery from injury. Thigh strength can be directly assessed using dynamometry or clinical tasks such as jumps and hops, although in the case of injured individuals such approaches may not be safe. In these cases, it is inferred that the muscle size is indicative of muscle strength thus allowing muscle size to serve as an indirect measure of muscle strength. Typically indirect clinical measures may poorly differentiate muscle size. A more muscle-specific clinical measure can be made from measuring the thickness of the quadriceps and hamstrings using clinical ultrasound. Typically, the individual muscles of the quadriceps and hamstrings are grouped together to assess thickness and the correlation between these thicknesses and muscle strength is well understood. The relationship between individual muscle thicknesses and the strength of their muscle groups as a whole is not well understood. The aim of this study was to test whether or not knee extension and flexion strength are correlated to the thickness of individual muscles in the quadriceps or hamstrings, respectively. This would allow clinicians such as athletic trainers to quickly assess atrophy and therefore loss in strength in injured athletes. Results demonstrated that both medial and lateral quadriceps and hamstrings thicknesses were moderately correlated with knee extension and flexion strength measures, respectively. Further analyses showed that grouping multiple quadriceps or hamstrings in the correlation did not improve the relationship of strength to

individual muscles. These results indicate that individual thigh muscle thicknesses correlated with knee strength similarly to one another. These results support prior research that has looked at each of these muscles as groups and carry implications about how clinicians can quickly measure muscle strength indirectly in populations where direct strength assessment is not possible.

INDIVIDUAL MUSCLE THICKNESS OF THE QUADRICEPS AND HAMSTRINGS AND THEIR RELATIONSHIP WITH KNEE EXTENSION AND FLEXION STRENGTH

by

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APPROVAL PAGE

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CHAPTER I

INTRODUCTION

Thigh strength is an essential measure for athletic performance in athletes, as well as recovery from injury and disease. A wide range of clinicians and strength and conditioning experts incorporate thigh-strengthening activities into the daily routine of their patients and clients. Greater thigh strength improves indicators of athletic performance such as squat max, sprint time, pro-agility tests, and time-to-fatigue across various sports, such as rugby, cycling, skiing, strongman, and Nordic Combined (Wang et al., 2016; Rønnestad et al., 2010; Losnegard at al., 2011; Winwood et al., 2012; Rønnestad et al., 2012). Symmetrical isokinetic (dynamic) strength between injured and uninjured quadriceps and hamstrings (injured has 85-90% strength of uninjured) has also been shown to be an indicator of return to play eligibility (Ménétrey et al., 2014). In fact, it has been shown that as it relates to the injury of the thigh, isometric (static) strength of the injured limb proportional to the uninjured limb is a better indicator of return-to-play eligibility than time away from sport (Moen et al., 2014). Collectively this indicates that development and subsequent assessment of thigh strength is a critical component of patients and clients.

Strength can be directly assessed in a variety of ways. Directly, isolated strength of a muscle group can be tested in a lab or clinical setting using instrumented dynamometry. Instrumented dynamometry is the measurement of force produced with hand-held or freestanding instrumentation such as a Biodex Dynamometer (Koutedakis & Sharp, 2004). Likewise, strength of the thigh can be assessed with functional tasks such as single leg hops, countermovement jumps, vertical jumps, and many other methods (Pyne et al., 2006). Lab standards of isokinetic and isometric knee flexion and extension are correlated with one-legged hop testing and jumping ability (Nyberg et al., 2006) (Järvelä et al., 2002). Thus, there appears to be a degree of relationship between different methods of strength assessment.

However, many of these functional thigh strength tests can put the integrity of the tissue at risk when dealing with an injured population as they may place undo/unsafe loads upon healing passive tissues. For example, in ACL reconstruction patients, it has been reported that depending on the surgeons and other clinicians involved, strength testing should not be incorporated in any form for anywhere from 3 to 8 weeks post-surgery and higher impact measures may not be incorporated for up to 12 weeks (Feller et al., 2002). While there are cases and situations when strength should not be directly assessed during a certain stage of injury/illness care, there are indirect measures of strength than can prove valuable for populations like these.

Indirect measures of thigh strength include anthropometrics, or the size measures of the human body. The traditional clinical anthropometric measure representative of thigh strength is thigh girth, or the circumference of the thigh as measured with a flexible tape measure (Gross et al., 1989). This measure is designed to represent the size of the muscles of the thigh, specifically in terms of cross-sectional area. This measure, although quick and easy for clinicians, is not a true measure of cross-sectional area of the muscles of the thigh since it ignores fat and bone as parts of the measure (Brozek et al., 1953). Thigh girth has been shown to indirectly estimate strength of the knee extensors and flexors in resistance trained athletes (Mayhew et al., 1993), but this does not seem to apply to all populations, such as those with greater adipose tissue as well as women (Brozek et al., 1953; Hosler et al., 1977). There is no way to tell with thigh girth if someone's thigh is large due to fat or skeletal muscle (Schantz et al., 1981). Skeletal muscle, being the only contractile tissue involved, is the target tissue to be measured. Since skin, fat, and other subcutaneous tissues are included, thigh girth fails to accurately measure thigh muscle cross-sectional area in many cases (Schantz et al., 1981).

Modern imaging techniques such as computed tomography (CT), magnetic resonance imaging (MRI), dual-x-ray absorptiometry (DXA), and ultrasound are all capable of assessing thigh girth, thigh muscle cross-sectional area, and fat content (Dupont et al., 2001; Worsley et al., 2014; Malkov et al., 2015). While all are medically available, ultrasound is likely the most clinically available, cost-effective, and patient-safe imaging modality. Ultrasound is a common imaging tool in clinical settings (Seymour et al., 2009). Specifically ultrasound is able to reasonably match the gold standard of MRI in measuring the cross-sectional area of muscles with fairly low cost (Worsley et al., 2014; Noorkoiv et al., 2010). Clinicians today often have access to ultrasound, and the cost of imaging with ultrasound is relatively low as compared to MRI.

Ultrasound has been established as a viable measurement tool of individual quadriceps and hamstring muscles as compared to magnetic resonance imaging (MRI) and computed tomography (CT) (Dupont et al., 2001). Ultrasound is particularly well established as a viable measure of cross-sectional area, the measure of muscle size of particular interest to this study (Walton et al., 1997; Lima et al., 2012; Ahtiainen et al., 2010). However, many clinical ultrasound machines are incapable of measuring cross-sectional area of thigh muscles because the ultrasound field of view is too small relative to the size of the knee extensors and flexors (Abe et al., 2015). It is possible in these clinical scenarios to measure knee extensor and flexor muscle thickness as a one-dimensional representation of the two-dimensional cross-sectional area. Ultrasound-based muscle thickness measures can accurately measure thickness of the knee extensors and knee flexors (Abe et al., 2015, 2016). Muscle thickness measures have also been found to indirectly indicate muscle strength and performance, much like cross-sectional area (Moreau et al., 2010).

However, it is still unknown as to if individual muscle morphology is more directly associated with knee extensor and flexor strength than the common clinical measure of thigh girth. It is important to establish the most accurate and clinically accessible indirect measure of thigh strength. Specially, determining the importance of individual components of quadriceps and hamstrings to their respective strength producing capacity about the knee will refine clinical practice. Further, in simple tasks such as knee extension and knee flexion, it is still not known which individual muscles are most closely associated with the strength of their respective groups. Some data indicates that post-ACL reconstruction patients having gone through a rehabilitation program still have significantly lower muscle volume in the vastus medialis muscle in the injured versus uninjured limb, suggesting that the vastus medialis may be more greatly affected by certain injuries than other muscles in the quadriceps (Marcon et al., 2015a, 2015b). However, other data suggests that the vastus lateralis muscle may be the greatest atrophied muscle in non-copers after ACL tears without reconstructive surgery (Williams et al., 2005). In regards to the hamstrings, some data suggests that the biceps femoris muscle changes its pennation angle and that, possibly as a result, the overall knee flexor strength decreases (Timmins et al., 2016). However, none of these studies describes how individual muscle size is representative of strength of the respective group as a whole.

Thus clear evidence still does not exist to answer whether the thickness of one or more thigh muscles may be most closely correlated with knee strength. The purpose of this study was to determine the relationships of thicknesses of vastus medialis and vastus lateralis to knee extension strength as well as semitendinosus and biceps femoris long head to knee flexion strength. It was hypothesized that the VM, VL, ST, BFLH muscle thicknesses would all be individually associated with strength of their respective actions about the knee. It was further hypothesized that the vastus medialis would be more closely associated with knee extensor strength than the vastus lateralis since the vastus medialis is the most affected after reconstructive surgery and rehabilitation (Marcon et al., 2015a, 2015b). It was further hypothesized that the lateral hamstrings would be more closely associated with knee flexor strength than the semitendinosus since such great architectural changes in the biceps femoris occur alongside knee flexor strength deficits (Timmins et al., 2016).

CHAPTER II

REVIEW OF THE LITERATURE

Overview

This literature review will begin by discussing the relationship between thigh strength and athletic performance. In terms of rehabilitation, the literature review will discuss the association between strength and recovery from injuries related to the muscles of the thigh and surrounding structures and will demonstrate the need for strength as a measure of functionality and return to play eligibility. Then the review will discuss the association between thigh strength and thigh muscle size as measured by muscle thickness. The literature review will then discuss anthropometric measures as they relate to the thigh. Finally, the literature review will end with a summary of gaps currently not covered in the literature.

Thigh Strength in Relation to Athletic Performance

It is generally accepted that strength is an important factor in athletic performance. Common clinical thought suggests that stronger athlete is often thought to be a more effective athlete. Isolated joint strength can be readily tested in a lab setting by testing the maximal voluntary force produced by a muscle group either isometrically (without movement) or isokinetically (movement at the same speed) (Wang et al., 2016; Rochcongar., 2004). The large, sagittal plane thigh muscles comprise the fundamental muscle groups of the quadriceps and hamstrings. These groups are often targeted in training, rehabilitation, and testing of the knee (Dowson et al., 1998). Understanding the relationship of isolated knee joint strength to athletic performance is an important concept for athletic trainers, team physicians, and other clinicians.

Strength training can improve athletic performance in multiple ways. Through isokinetic and Wingate testing in football players, it was reported that greater thigh muscle strength measured through isokinetic knee flexion and extension tasks was predictive of greater anaerobic performance, a key factor in many athletics. Specifically, football players with greater isokinetic peak torque of the knee extensors had higher anaerobic performance in a Wingate test (Kin-Isler et al., 2008). It has also been shown that training programs that focus to improve whole, functional thigh muscle strength are also associated with improved performance, making it further evident that strength plays a major role in athletic performance. For example, in a 12-week resistance-training program, Nordic Combined athletes on a whole-body strength training program that included the deep squat as the lower body component were able to greatly improve squat one-rep max as well as squat-jump height (key indicators of athletic performance) without sacrificing endurance or VO_2 max (Rønnestad et al., 2012). In another 12-week resistance program which included half squats at submaximal and maximal loads, elite cross-country skiers improved VO_2 max significantly more by training for strength than in a running program alone (Losnegard et al., 2011). Thus, strength training appears to be beneficial toward direct sport performance.

Strength has also been shown to improve performance in functional testing. One such example assessed the relationship of various hop tests to isometric muscle testing of knee flexors and extensors (Kollock et al., 2015). Since isometric and isokinetic testing may not always be the most practical methods for clinicians, these functional tasks were tested to see if they correlated with thigh strength. In this recreationally active population, knee flexor peak isometric force was correlated to single-legged vertical jump height (r^2=0.42, p≤0.01), a common functional measure. Likewise, knee extensor peak force was somewhat correlated (r^2=0.31, p<0.05) with single legged vertical jump for work, but most correlations for knee extensors were either non-significant or not strong (Kollock et al., 2015). However, it should also be noted in the context of performance that a study reported that isokinetic knee flexion and extension of master's level swimmers was not associated with swim time (Magnusson et al., 1995). This study may have been confounded by a lack of injury history and the types of swim events ranging from sprinters to middle and long distance events. Another study investigated the effects of a ten-week training program that included squats as well as knee flexion-extension, on cycling performance. The study was performed on recreationally active individuals and consisted of a pretest-posttest design with strength training as the treatment. It was reported that a strength training program lasting ten weeks (three days/week) of isolated repetition training of the knee extensors and flexors at 80% of the one-rep max increased one-rep max squat, isolated knee extension, and isolated knee flexion by an average of 30%, while also improving endurance in cycling and running by increasing time to exhaustion at 80% of the VO2 max (Hickson et al., 1988). Collectively, this literature suggests that thigh strength plays an essential role in various aspects of athletic performance, from anaerobic performance to clinical testing to functional endurance.

Thigh Strength in Relation to Recovery from Injury

Thigh strength training is commonplace in recovery/rehabilitation programs following injury and/or surgery. Studies often seek to gauge recovery and return to function of injured limbs after surgery based on their strength (Jenkins et al., 2011; Gadea et al., 2014). After significant knee injury, such as an ACL tear, it is common to compare the strength of the injured limb in knee flexion and extension to the strength of the uninjured limb as a relative strength marker. One study used a knee flexion task measuring maximal isometric strength of the injured to the uninjured limb after ACL reconstruction to gauge recovery (Timmins et al., 2016). Another study suggests that as the uninjured limb does not sustain strength deficits, it can remain a reasonable comparison for the injured limb (Hiemstra et al., 2007). Yet another study evaluated rehabilitation training outcomes over three years with 43 patients having encountered knee injuries. The study found that isokinetic knee flexion and extension strength training after injury are effective in reducing pain after debilitating knee injury, further indicating recovery (Gadea et al., 2014). These evaluations help to show how well an athlete is adapting in their rehabilitative program, hopefully leading them to recovery and return-to-play.

When an athlete is injured and goes through recovery, eventually there are return-to-play evaluations that look at various aspects of an athlete's health and fitness in order to determine if they are ready to engage in sport without serious risk of further injury. Thigh strength testing is advocated in return to play testing to determine the muscular rehabilitation of the athlete (Panariello, et al., 2016). These tests are considered foundational for fitness and include isolated isokinetic testing, hop tests, and jump tests (Panariello, et al., 2016). Although this study focused on dynamometry measures, it should be noted that there were significant associations between isolated dynamometric measures and some functional test performances (Kollock et al., 2015; Manske et al., 2003). However, this may not imply that functional tests and single-joint isolated dynamometry should be used interchangeably (Östenberg et al., 1998; Manske et al., 2003). A systematic review of return-to-play data involving post ACL reconstructed athletes found that across 45 studies, isokinetic strength deficits, particularly in knee flexion, were the most common clinical sign. This led the researchers to conclude that isokinetic knee strength may be one of the most important factors in return-to-play criteria (Petersen et al., 2014). This conclusion is in agreement with other data that have illustrated a link between recovery from surgery and symmetry of strength in the quadriceps between the injured and uninjured limb (Ménétrey et al., 2014; Jamshidi et al., 2005). In a review of the literature regarding patellar dislocations, it was found that across studies, return-to-play criteria consistently included return to relative symmetry in strength between the injured and the uninjured limbs (injured has 85-90% strength of uninjured) particularly in the quadriceps. These strength tests included isokinetic knee flexion and extension tasks as well as dynamic strength tests such as the single leg squat (Ménétrey et al., 2014). Collectively, isokinetic and isometric knee strength tests are essential return-to-play strength assessments and can be considered indicators of functional tasks as well.

With this understanding of how strength contributes to other aspects of performance, it is also important to understand what makes one muscle or muscle group stronger than another. Various physical measures can influence the strength of muscles and muscle groups. These physical measures can then be used as indirect estimates of strength and are known as anthropometrics. Indirect anthropometrics include height, body mass, and thigh girth; while direct anthropometric include skeletal muscle volume, cross-sectional area, and thickness.

Indirect Anthropometric Muscle Measures

Anthropometrics play a key role in the expression and assessment of thigh strength. Anthropometry is the measurement of various aspects of the human body. Examples commonly reported in the strength literature include height, body mass, thigh circumference (girth), body fat percentage, and muscle cross-sectional area. Muscle girth and cross sectional area are two anthropometric measures that are commonly used to assess the size and/or strength of muscle (Fornusek et al., 2013; Hosler, 1977; Affara et al., 2013). These measurements are of interest because they help determine the morphology of the muscle, a source of the strength discussed above.

Thigh girth may be the most common clinical anthropometric measure of thigh musculature. Thigh girth is the circumference of the thigh (often around the mid-thigh) to estimate muscle mass (Brozek, 1953). In one training study, patients having incurred spinal cord injuries were put through a training program on isokinetic cycle ergometers in order to induce strength gains and hypertrophy. Pre and posttest measures of strength were assessed with isometric dynamometry and thigh girth at the middle and distal thigh.

After six weeks, it was found that strength and thigh girth both improved, supporting that strength gains were due not only to neurological adaptations, but muscle size increases as measured by thigh girth (Fornusek et al., 2013). Another study using power lifters and bodybuilders tested maximal isometric force of the knee extensors as well as thigh girth. It was found that thigh girth was correlated with maximal force ($p<0.001$) (Häkkinen et al., 1984). Thus, thigh girth may have some predictive value of strength.

However, there are times when a training study reveals that thigh girth may or may not increase along with strength. Another study that only partially supports thigh girth as an estimate of strength performed a seven-week resistance-training program in healthy men and women and measured both strength and thigh girth at the beginning and end of the training program. Strength was tested using isometric dynamometry and thigh girth was tested using the circumference at the superior thigh, just over the rectus femoris muscle body. The training program included half squats and leg extensions to train the quadriceps. At the end of the study, both strength and thigh girth increased in men; which would support the theory that thigh girth reflects muscle mass of the thigh and therefore strength. However, thigh girth did not significantly increase in women, even though strength did; the researchers therefore speculated that fat mass decreased in women while muscle mass increased and thigh girth was therefore not changed (Hosler., 1977). It should be noted that these studies are generally based upon athletic populations. In athletes, body mass and strength are often correlated, as athletes tend to have more fat free body mass and more specifically skeletal muscle mass than non-athletes (Midorikawa et al., 2007). If an obese, sedentary person were to be tested for performance and anthropometric measures, the correlation would likely decrease. A study that supports this compared subjects based on body fat percentage and thigh girth. It found that in a nonathletic population, thigh girth was not an accurate estimate of muscle cross-sectional area because of many subjects that had high levels of adipose tissue (Schantz et al., 1981). There currently is not a standardized body fat percent cut-off score that can tell the clinician when a simple tape measurement is accurate. Therefore, basic anthropometric measures like thigh girth or body mass can be inadequate predictors of performance and overall strength for certain individuals.

Clinically, thigh girth is simple and cost-effective, but has some clear limitations. For example, a study used various demographic and anthropometric data to predict isokinetic knee flexion and extension, including (but not limited to) thigh girth. Knee torque could only be predicted by including factors like age, sex, height, and weight, having made a predictive equation that accounted for 64-76% of the total variance in knee extension and flexion. In the same study, looking at a post knee injury population found that not including thigh girth or body fat, but keeping age, sex, height, and weight still accounted for 61-76% of the variance (Gross et al., 1989). This brings into question the value of thigh girth as an anthropometric measure to accurately predict thigh muscle function. One of the biggest faults in thigh girth as a measure of muscle function is that it does not differentiate fat and muscle content. Most studies that include thigh girth also address fat content through skinfold measures in order to improve accuracy (Brozek., 1953; Schantz et al., 1981; Hosler., 1977). In comparing literature that factors body fat in thigh girth against literature that does not, one study reported that thigh girth alone could not accurately predict fat mass, muscle mass, or bone mass ($p>0.05$) (Tresignie et al., 2012), while another study using MRI found that taking body fat into account allowed for thigh girth to have a strong correlation to muscle cross-sectional area ($R>0.96$) (Housh et al., 1995).

The other primary limitation of using girth as an indicator of muscle function is that individual muscle size is ignored with this measure, which can impact the of understanding of the relationship between muscle size and strength in the thigh (Schantz et al., 1981). The two biggest limitations with using thigh girth as an indicator of strength are 1) Thigh girth does not factor the size of *individual* muscles and 2) Thigh girth does not look specifically at muscle, but at the size of the fat and bone (non-contractile tissues) as well. The following section will highlight the importance and need of assessing individual muscle size in predicting strength and functionality.

Height and Body Mass as Indirect Anthropometric Measures

Anthropometry/morphology plays a role in thigh strength. Height is typically considered to affect the length of the thigh and therefore the length of thigh muscles. A taller person likely has a longer thigh and therefore a longer thigh muscle (Handsfield et al., 2014). This could potentially alter the morphology of the muscle and affect measurements when comparing taller subjects to shorter subjects (Kluka et al., 2016). In order to make taller and shorter subjects comparable in the same study, this is controlled for in studies by measuring height of the subject or femur length (Palmer et al., 2014).

Likewise, body mass is considered to be an important anthropometric measure, since a bigger person from a homogenous population should have larger thigh muscles and therefore more contractile units, assuming homogeneity in muscle quality and training status. As an example, body mass has been found to be a predictor of squat strength (Caruso et al., 2009). There are studies that suggest that simple anthropometric measures such as upper or lower body mass are predictive of performance, but these still suggest that strength needs to be factored in as well. For example, one study on strongman performance found that factoring both overall body mass and squat strength could strongly predict maximal repetitions for time in key events such as tire flips, log clean and presses, truck pulls, and farmer's walks (r=0.87), but that factoring squat alone could predict performance as well (r=0.61-0.85). The authors state that although this makes a case for anthropometrics being included as a factor, it is clear that they cannot fully predict performance without strength (Winwood et al., 2012). Another study found that speed in cricket bowling (a task requiring both upper and lower limb contributions) could be predicted by including anthropometric factors such as body mass, percent muscle mass, and height, but also required input of static jump height as a strength measure (r=0.86 when combined) (Pyne et al., 2006). Although indirect anthropometrics may be able to predict some aspects of strength and performance, it is clear that there is not a reliable way in which to predict strength for all subjects with these indirect measures. More direct measures of the muscles involved in these movements are needed.

Direct Anthropometric Muscle Measures

It is well established that an increase in muscle size increases the ability of the force producing capability of the muscle in a linear relationship (Maughan et al., 1983, 1984a, 1984b; Mayhew et al., 1993). This has lent credence to the use of overall thigh girth as a measure of muscle size (Willan et al., 2002). But with modern imaging techniques, we are able to discern muscle tissue so as to avoid counting subcutaneous fat as muscle in thigh measures. One method of measuring size of an individual muscle or muscle group is to look at its Cross Sectional Area (CSA) (Marcon et al., 2015a, 2015b; Hacker et al., 2016). CSA is the area of a section in the muscle if it was bisected. This allows for a direct measure of muscle "size".

Cross-sectional area of muscle is generally divided into two categories – anatomical cross-sectional area (aCSA) and physiologic cross-sectional area (pCSA) (Blazevich et al., 2009; Abe et al., 2016). Anatomical cross-sectional area is the simplest and is defined as the cross-sectional area of the muscle as measured perpendicular to the limb. Physiologic cross-sectional area is more complex in that it requires the measurement of CSA to be taken perpendicular to the pennation of the muscle fibers themselves (Narici et al., 1992; Connolly et al., 2011). Both are used in literature and although it has been assumed in the past that pCSA would be more accurate, there is evidence that aCSA and pCSA, when measured at the same location in the thigh, are not significantly different and can be used interchangeably (Connolly et al., 2011).

CSA is typically measured as the section with the largest circumference in the muscle where it could be bisected. This is found in cadaveric models by cutting the thigh transversely and physically measuring the muscles (Willan et al., 1990, 2002). However, in-vivo this is not a viable method to obtain CSA. Rather than cutting into the thigh at these points, imaging techniques like MRI and ultrasound can be used to take images of the peak CSA for muscle groups or individual muscles (Worsley et al., 2014). Although

MRI is the gold standard for imaging, it is relatively expensive and is often not readily available in the clinical setting. Ultrasound (US), however, is reliable in its ability to measure cross-sectional area (a two-dimensional measure) as compared to both MRI and CT (Dupont et al., 2001; Noorkoiv et al., 2010). Importantly it is easier to gain access to US and US is easier learn to use clinically, and is much less expensive than MRI or CT (Walton et al., 1997; Worsley et al., 2014). Ultrasound, then, may be the tool of choice for this study to establish the relationship of individual muscle CSA to strength.

The relationship between CSA and strength is well established. As muscle cross-sectional area increases, strength increases (Palmer et al., 2014; Lima et al., 2012). An ultrasound study of the rectus femoris reported that muscle CSA and maximal isometric knee extensor strength were strongly correlated ($r=0.78$, $p<0.001$), demonstrating that one muscle can determine an association of strength of the entire quadriceps (Seymour et al., 2009). However, none of the other quadriceps were compared, so this study does not describe which of the quadriceps could best describe the strength of the knee extensors as a whole. Further tying strength to CSA, a study performed on cyclists found that strength training significantly increased total thigh muscle CSA as measured with magnetic resonance imaging. No regard was given to individual muscles. Maximal knee extensor isometric force and power also improved as measured in Wingate test, both considered to be indicators of overall cycling performance and yet the article states that body mass did not statistically increase ($p>0.05$) (Rønnestad et al., 2010). This further emphasizes that basic anthropometric measures such as body mass (which didn't increase) cannot predict strength (which did increase) to the same extent as CSA (which also increased). Although in the opposite direction, but explaining the same directional relationship of CSA and strength, another study found that as quadriceps total muscle CSA decreased with age, maximal isometric strength decreased. The study looked at muscle CSA in knee extensors and the subsequent relationship with maximal isometric force ($r=0.82$, $p<0.001$). It was reported that muscle atrophy with older age led to decreased cross-sectional area of the knee extensors and maximal isometric strength proportionally decreased across three age ranges, from 26-35 years ($r=0.72$, $p<0.01$), 46-55 years ($r=0.86$, $p<0.01$), and 66-75 years ($r=0.67$, $p<0.05$) (Häkkinen & Häkkinen., 1991). Collectively this work suggests that the variables of thigh muscle cross-sectional area and strength are moderately correlated in a linear model. Although not predictive of knee extension/flexion strength, CSA appears to account for a significant portion of the variance.

The use of CSA to predict muscle performance is not without limitations. A review of literature suggested that cross-sectional area has limitations in predicting muscular performance due to factors that include training level, gender, and age (Jones et al., 2008).

More importantly is the clear lack of comparisons between individual muscles in these studies. For example, one study discussed earlier used rectus femoris to find correlates between individual muscle CSA and strength (Seymour et al., 2009), but didn't look at other individual quadriceps muscles. Another study looked at vastus lateralis cross-sectional area to measure muscle growth, but also ignored other muscles in measures of CSA (Walker et al., 2013). Previous work in using individual quadriceps and hamstring muscle CSA is quite limited. These muscles have already been noted in cadaveric studies to have variation in cross-sectional area between one another as well as between subjects (Willan et al., 2002, 1990). In addition to this, there are potential biomechanical advantages to certain muscles in both the quadriceps and hamstrings in their respective moment arms (Wilson & Sheehan, 2009; Herzog & Read, 1993). Moment arms are distances from the joint axis to the lines of force coming from the muscles that mobilize the joint. It has already been found that individual quadriceps and hamstrings have different moment arms, that these moment arms can alter muscle architecture at different angles of flexion, and that these moment arms could potentially affect individual muscle contributions to movement (Wilson & Sheehan, 2009; Herzog & Read, 1993; Obrien et al., 2009; Kellis & Baltzopoulos, 1999). The most important area in which this study differs from prior research is in the comparison of individual muscles in the quadriceps femoris and hamstrings.

There is one further issue with the studies heretofore mentioned, which is that many clinical ultrasound machines cannot measure static CSA of large muscles, especially of those in the thigh, because clinical ultrasound transducers are often too small to pick up such a large image (Abe et al., 2015). However, just as cross-sectional area is a measure of muscle size at one point, another measure of muscle size is muscle thickness. Muscle thickness is a measure of the size of a muscle in the form of a line from superficial to deep borders of the muscle (Freilich et al., 1995; Abe et al., 2016, 2016). Where cross-sectional area is a two-dimensional measure of the muscle, muscle thickness (MT) is a one-dimensional measure of muscle thickness, which has been found to be linearly related to CSA of the quadriceps ($r=0.91$, $p<0.001$) as well as the hamstrings ($r=0.848$, $p=0.002$) (Abe et al., 1997, 2015, 2016).

The relationships of knee extensor and flexor muscle thicknesses to thigh strength are similar to correlations of thigh strength to CSA. One study determined that mid-thigh individual quadriceps thicknesses significantly correlated to a knee extensor MVIC ($p<0.001$-0.0001) (Freilich et al., 1995). Another study reported that vastus lateralis, but not rectus femoris muscle thickness, was predictive of maximal isometric knee extensor torque ($R^2=0.91$, $p<0.05$) (Moreau et al., 2010). Since MT is a clinically, more efficient methods to use, it will be used to represent muscle size in this study.

Current Gaps in the Literature

As mentioned above, other measures of muscle size in the thigh have ignored individual muscles. This is often the case even in studies where the muscle is imaged. Some studies have looked at the quadriceps as a whole and attempted to estimate contributions to force by looking at pennation angles, but did not directly assess peak CSA of the individual muscles and then calculate the subsequent association with strength (Narici et al., 1992). Other studies look to vastus lateralis as a determinant/indicator of overall quadriceps strength (Pareja-Blanco et al., 2016; Mangine et al., 2014). However, data is also present which reports vastus medialis atrophy as a significant factor in several conditions, including patello-femoral pain syndrome (Pattyn et al., 2011) and post-ACL reconstruction patients (Marcon et al., 2015a, 2015b). There is also EMG data suggesting that vastus medialis is a reasonable estimate of total contractile force of the knee extensors (De et al., 2008). This brings the question as to how the individual muscle sizes/functionalities are representative of the collective group force generating capacity.

CHAPTER III

METHODS

Participants

Thirty two young (18-30yrs), recreationally active males (n=15) and females (n=17) were recruited in this study to find associations between thigh muscle thickness and thigh isokinetic and isometric strength. Recreationally active was defined as participating in aerobic and/or resistance training exercise at least 3 times per week for at least 30 minutes per session (Schmitz et al., 2004). This age-range helped control for muscle density, since inactive subjects may have more intramuscular fat and lower muscle quality (Hogrel et al., 2015; Häkkinen & Häkkinen., 1991; Malkov et al., 2015). A priori power calculations demonstrated that an effect size of ρ=0.5 and an alpha of P <0.05 would us 85% power using 30 participants. Previous studies looking at individual muscle size found significant results using 30 total subjects (Maughan et al., 1983; Willan et al., 2002). Participants first gave written informed consent.

Procedures

Data was gathered over 48 hours of testing. On day one, subjects signed all consent forms, were familiarized with all procedures, had muscle thickness data gathered, and were trained to perform maximal voluntary isometric contractions (MVIC) and isokinetic contractions. This initially consisted of placing the participant in the Biodex System 3 dynamometer exactly as they would be during trials for data. Then participants performed 3 submaximal repetitions at 25%, 50%, and 75% of their perceived maximal effort and then 3 repetitions at maximal effort. Verbal feedback and encouragement were given during each trial. If a participant did not appear to appropriately perform a true MVIC, correction was given before the next trial until the participant gave two consistent MVICs.

Figure 1. Maximal Knee Extension and Typical Set Up for Subject in Biodex

Isokinetic training was also done, with subjects performing 6 total practice repetitions. Participants were placed in the Biodex System 3 dynamometer exactly as they would be during trials for data. Then participants performed 3 submaximal repetitions at 25%, 50%, and 75% of their perceived maximal effort and then 3 repetitions at maximal effort. Verbal feedback and encouragement were given during each trial. Once again, correction was given until two maximal trials were consistent in torque production. Muscle thickness values were obtained on both days because of the need to establish intratester reliability between days.

On day two, subjects had anthropometrics (height, weight, and muscle thickness (MT)) assessed and performed the MVIC and isokinetic protocols for muscle strength as described below (Schmitz et al., 2000). When asked, no subjects noted feeling sore from the prior testing session.

Strength Assessment

Both isometric and isokinetic strength were tested; with isometric strength measured first and isokinetic second (Shultz et al., 2009). Following a 5-minute warm up on a cycle ergometer, knee extension and flexion maximal voluntary isometric contraction (MVIC) torque (Nm) were tested using a Biodex System 3 dynamometer (Biodex Medical Systems Inc.; Shirley, NY). The dominant limb (defined as the stance limb when kicking a ball) of subjects was tested. Knee extension and flexion MVICs were obtained at 60° and 45°, respectively (Murray et al., 1977). The back of the seat was set to 100°. The axis of rotation of the dynamometer was in line with the lateral epicondyle of the femur and the resistance pad will be placed 2 inches above the ankle joint (Shultz et al., 2009). Participants sat with their arms across their chest and verbally encouraged during the procedure to kick or pull for knee extension or flexion, respectively (Shultz et al., 2009). Participants performed three preparation trials at 25%, 50%, and 75% of the perceived maximal contraction; then at 100% for three 5-second MVIC trials with 60 seconds of rest between trials (Montgomery & Shultz, 2010;

Kollock et al., 2015). After a 5-minute rest period, isokinetic strength was tested (Schmitz & Westwood, 2001).

Figure 2. Isokinetic Knee Extension/Flexion and Typical Set Up for Subject in Biodex

Isokinetic testing was performed with the subject seated in the dynamometer with the seat set to 100° (Schmitz & Westwood, 2001). Isokinetic knee extensor and flexor torque (Nm) was tested between 0° and 90° of knee flexion with Biodex System 3 dynamometer. The participants performed 5 warm-up repetitions at submaximal and maximal effort and then performed 5 trials of maximal effort at 180°/s, which has been used in studies testing isokinetic strength and has similar results to speeds of 120°/s and 60°/s (Kollock et al., 2015; Tsiokanos et al., 2002; Schmitz & Westwood, 2001).

Assessment of Muscle Thickness

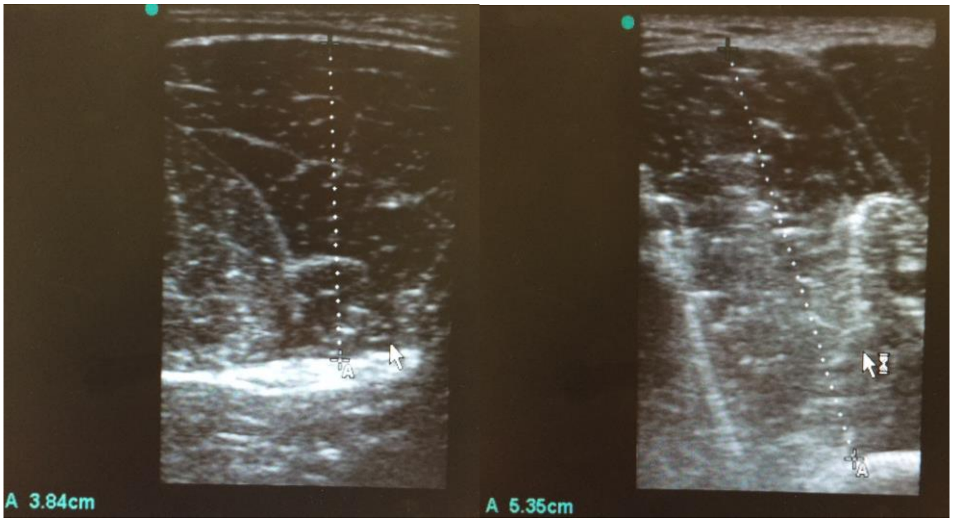
All quadriceps muscle thicknesses were measured along the circumference of the individual muscle bellies at the point 50% the length of the femur between the greater trochanter and lateral condyle of the femur (Abe et al., 2015) while all hamstring muscle thicknesses were measured along the circumference of the individual muscle bellies at the point 60% the length of the femur from the greater trochanter to the lateral condyle of the femur (Abe et al., 2016) and measured using real-time B-mode SonoSite MicroMaxx ultrasound with the HFL38/13-6 MHz transducer. A marker pen was used to mark the greater trochanter and lateral condyle when found in order to make it easier to find the imaging site when ready (Abe et al., 2016). A tape measure was used to provide an outline marked with the pen around the thigh at 50% and 60% lengths in order to provide a constant reference during imaging. The specific muscles measured were the vastus medialis, vastus lateralis, semitendinosus, and biceps femoris long head (Abe et al., 2015, 2016).

For imaging the quadriceps, the participant was seated in a relaxed position in the Biodex System 3 dynamometer and the knee was placed in the same 60° knee flexion as the isometric test so as to make the measurement more accurate to the task (Sogabe et al., 2009; De et al., 2008; Hacker et al., 2016). For imaging the hamstrings, the participant laid face down on the Biodex and have their knee held steady in 45° of flexion (confirmed with a goniometer) to best mimic the positioning of the limb in the isometric task. Subjects were asked to simply sit quietly and relax in order to make measurements consistent and unaffected by perturbations.

Figure 3. Positions for Ultrasound Assessment of Thigh Muscle Thickness

The caliper function on the SonoSite MicroMaxx was engaged and the muscle thickness was recorded as the average distance in centimeters of three repeated measures from the superficial border of the muscle belly to the deep border of the muscle belly. This was found by identifying the medial and lateral borders of the individual muscles, finding the halfway point between the two, and measuring from superficial border to deep border of each muscle. The line of sight was drawn to the nearest point of the deep border of each muscle (Moreau et al., 2010; Abe et al., 2014, 2015, 2016; Freilich et al., 1995). This helped control for muscles that do not make contact with the femur at certain lengths. This procedure was repeated on day 1 and day 2 to allow for establishment of intratester between day measurement consistencies.

Figure 4. Ultrasound Images and Measurements of Individual Hamstrings (Left, Biceps Femoris Long Head) and Quadriceps (Right, Vastus Medialis)



Data Reduction, Collection, and Analysis

The Biodex System 3 dynamometer was connected to a computer to record torques (Nm) from respective tests. For the MVIC trials, the highest peak value obtained over the 5 sec MVICs was used for analyses. For the knee extension and flexion isokinetic trials the peak torque was measured as the angle-specific torque at 60° and 45° of knee flexion, respectively. Data was imported into Microsoft Excel for further analysis.

The images used to measure muscle thickness of each muscle were imported into a computer to 2D SiteLink image analysis software in order to record results. Muscle thickness of each muscle was recorded for vastus medialis, vastus lateralis, semitendinosus, and biceps femoris in Microsoft Excel for analysis. The average of 3 measures at each site was included for analyses.

Data Analyses

Using muscle thickness data obtained on each day, intratester between day reliability and precision was established examining the $ICC_{2,3}$ and standard error of measurement for each muscle thickness.

All data was initially tested for normality using the Shapiro–Wilk test. Pearson correlations with an alpha level of ($P \leq 0.05$) were then run to determine if the medial or lateral quadriceps were able to determine the association knee extensor strength and if medial or lateral hamstrings were able to predict knee flexor strength. In order to provide a comparison of medial and lateral quadriceps, stepwise regression analyses were used to determine variance accounted for by each muscle. In the case of non-normally distributed data, Spearman-Rho correlations were completed.

CHAPTER IV

RESULTS

Demographics

Table 1. Demographic Information.

Demographics	Total	Male	Female
n	32	15	17
Age (yrs)	21.2 (3.2)	22.4 (3.6)	20 (2.3)
Height (cm)	173.7 (9.6)	179.3 (8.7)	168.8 (7.7)
Mass (kg)	74 (13.7)	80.7 (11.1)	68.2 (13.2)
Stance Limb	L = 28; R = 4	L = 13; R = 2	L = 15; R = 2
ST thickness (cm)	3.1 (0.6)	3.5 (0.5)	2.8 (0.4)
BFLH thickness (cm)	3.5 (0.5)	3.9 (0.4)	3.3 (0.4)
VM thickness (cm)	4.8 (0.5)	5.2 (0.4)	4.5 (0.4)
VL thickness (cm)	5.0 (0.5)	5.4 (0.2)	4.7 (0.5)
Isometric Extension Peak Torque (Nm)	218.2 (55.9)	251.8 (45.3)	188.6 (47.6)
Isometric Flexion Peak Torque (Nm)	107.6 (33.2)	130.1 (32.8)	87.7 (17.4)
Isokinetic Extension Peak Torque (Nm)	130.9 (33.8)	154.1 (29.7)	110.4 (22.2)
Isokinetic Flexion Peak Torque (Nm)	77.1 (24.2)	94.9 (22.6)	61.4 (11.3)

All Values are as “Mean (Standard Deviation)”.
Participant Demographics are Included in Table 1.

Reliability

Intratester, between-day reliability and precision (ICC±SEM) for thigh skinfold and thigh girth measures were assessed and were found to be reliable and precise (skinfold $ICC_{2,3}$ = 0.97±4.9mm; thigh girth $ICC_{2,1}$ = 0.94±1.4mm). Ultrasound measures were all found to be reliable and precise from day one to day two (ST $ICC_{2,3}$ = 0.95±0.2; BFLH $ICC_{2,3}$ = 0.93±0.2; VMO $ICC_{2,3}$ = 0.92±0.2; VL $ICC_{2,3}$ = 0.93±0.2). All ICC values were deemed within the "excellent" range for reliability (Cicchetti, 1994).

Analysis of Normality

Shapiro-Wilk tests revealed that data were normally distributed with the exception of isometric (P=0.04) and isokinetic flexion (P=0.04) peak torques. Therefore, Spearman-rho correlations were performed in place of Pearson correlations when using these variables.

Tests of Normality

Table 2. Tests of Normality for Muscle Thickness and Strength Measures.

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
ST2 Avg	.096	31	.200	.985	31	.934
BFLH2 Avg	.099	31	.200	.972	31	.564
VM2 Avg	.153	31	.061	.954	31	.201
VL2 Avg	.147	31	.085	.937	31	.067
isoMextPeakT (Nm)	.085	31	.200	.964	31	.367
isoMflexPeakT (Nm)	.147	31	.086	.928	31	.040
isoKextPK TQ (Nm)	.110	31	.200	.956	31	.231
isoKflexPK TQ (Nm)	.165	31	.031	.889	31	.004

ST2 Avg = Semitendinosus Thickness; BFLH2 Avg = Biceps Femoris Long Head Thickness; VM2 Avg = Vastus Medialis Thickness; VL2 Avg = Vastus Lateralis Thickness; isoMextPeakT = Isometric Extension Peak Torque; isoMflexPeakT = Isometric Flexion Peak Torque; isoKextPeakT = Isokinetic Extension Peak Torque; isoKflexPeakT = Isokinetic Flexion Peak Torque

A master correlation table is found in tables 3 and 4.

Statistical Correlations

Table 3. Pearson Correlations

Correlations

		ST2 Avg	BFLH2 Avg	VM2 Avg	VL2 Avg	isoMextPeakT (Nm)	isoMflexPeak T (Nm)	isoKextPK TQ (Nm)	isoKflexPK TQ (Nm)
ST2 Avg	Pearson Correlation	1	.732	.597	.564	.588	.666	.565	.550
	Sig. (2-tailed)		.000	.000	.001	.000	.000	.001	.001
	N	32	32	32	31	32	32	32	32
BFLH2 Avg	Pearson Correlation		1	.659	.660	.508	.597	.583	.504
	Sig. (2-tailed)			.000	.000	.003	.000	.000	.003
	N		32	32	31	32	32	32	32
VM2 Avg	Pearson Correlation			1	.689	.526	.522	.584	.379
	Sig. (2-tailed)				.000	.002	.002	.000	.032
	N			32	31	32	32	32	32
VL2 Avg	Pearson Correlation				1	.553	.400	.525	.387
	Sig. (2-tailed)					.001	.026	.002	.031
	N				31	31	31	31	31
isoMextPeakT (Nm)	Pearson Correlation					1	.758	.764	.587
	Sig. (2-tailed)						.000	.000	.000
	N					32	32	32	32
isoMflexPeakT (Nm)	Pearson Correlation						1	.643	.683
	Sig. (2-tailed)							.000	.000
	N						32	32	32
isoKextPK TQ (Nm)	Pearson Correlation							1	.735
	Sig. (2-tailed)								.000
	N							32	32
isoKflexPK TQ (Nm)	Pearson Correlation								1
	N								32

ST2avg = Semitendinosus Thickness, BFLH2avg = Biceps Femoris Long Head Thickness, VM2avg = Vastus Medialis Thickness, VL2avg = Vastus Lateralis Thickness, isoMextPeakT = Isometric Extension Peak Torque, isoMflexPeakT = Isometric Flexion Peak Torque, isoKextPKTQ = Isokinetic Extension Peak Torque, isoKflexPKTQ = Isokinetic Flexion Peak Torque

Table 4. Spearman-rho Correlations for Nonparametric Statistics

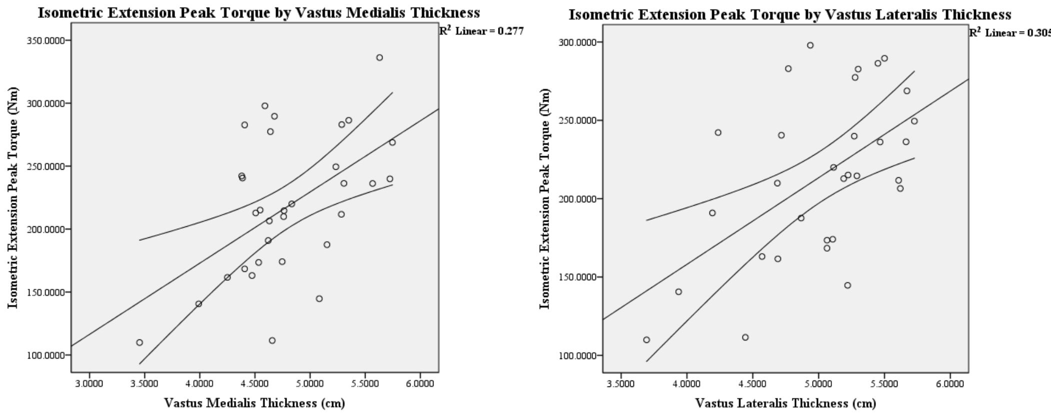
Correlations

			ST2 Avg	BFLH2 Avg	VM2 Avg	VL2 Avg	isoMextPeakT (Nm)	isoMflexPeak T (Nm)	isoKextPK TQ (Nm)	isoKflexPK TQ (Nm)
Spearman's rho	ST2 Avg	Correlation Coefficient	1.000	.696	.573	.546	.529	.664	.577	.646
		Sig. (2-tailed)	.	.000	.001	.001	.002	.000	.001	.000
		N	32	32	32	31	32	32	32	32
	BFLH2 Avg	Correlation Coefficient		1.000	.677	.589	.500	.628	.537	.529
		Sig. (2-tailed)		.	.000	.000	.004	.000	.002	.002
		N		32	32	31	32	32	32	32
	VM2 Avg	Correlation Coefficient			1.000	.633	.440	.501	.514	.515
		Sig. (2-tailed)			.	.000	.012	.004	.003	.003
		N			32	31	32	32	32	32
	VL2 Avg	Correlation Coefficient				1.000	.519	.522	.541	.519
		Sig. (2-tailed)				.	.003	.003	.002	.003
		N				31	31	31	31	31
	isoMextPeakT (Nm)	Correlation Coefficient					1.000	.843	.806	.625
		Sig. (2-tailed)					.	.000	.000	.000
		N					32	32	32	32
	isoMflexPeakT (Nm)	Correlation Coefficient						1.000	.786	.751
		Sig. (2-tailed)						.	.000	.000
		N						32	32	32
	isoKextPK TQ (Nm)	Correlation Coefficient							1.000	.805
		Sig. (2-tailed)							.	.000
		N							32	32
	isoKflexPK TQ (Nm)	Correlation Coefficient								1.000
		Sig. (2-tailed)								.
		N								32

ST2avg = Semitendinosus Thickness, BFLH2avg = Biceps Femoris Long Head Thickness, VM2avg = Vastus Medialis Thickness, VL2avg = Vastus Lateralis Thickness, isoMextPeakT = Isometric Extension Peak Torque, isoMflexPeakT = Isometric Flexion Peak Torque, isoKextPKTQ = Isokinetic Extension Peak Torque, isoKflexPKTQ = Isokinetic Flexion Peak Torque

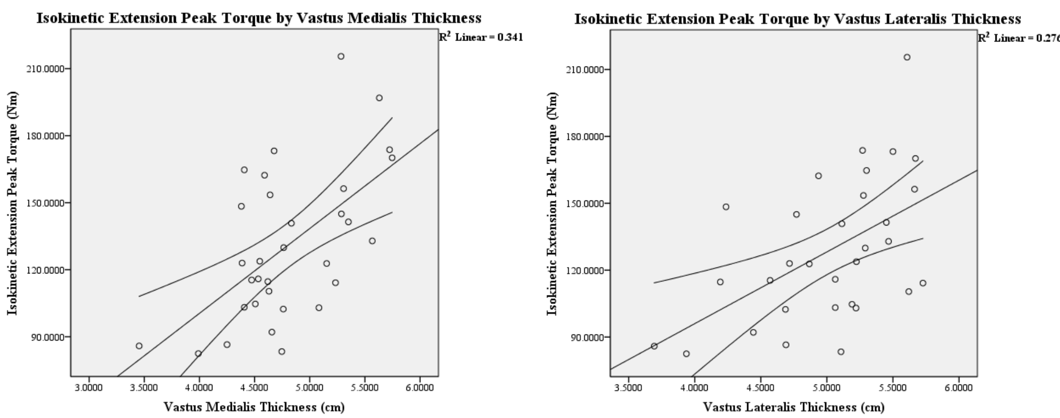
Pearson correlations of isometric extension peak torque revealed that VM (r=0.53, p=0.002) and VL (r=0.55, p=0.001) thicknesses were moderately correlated with isometric extension. Pearson correlations of isokinetic extension peak torque revealed that VM (r=0.58, p<0.001) and VL (r=0.52, p=0.002) thicknesses were moderately correlated with isokinetic extension. Scatter plots of extensor correlations are located in figures 5 & 6.

Figure 5. Relationship Between Vastus Medialis and Vastus Lateralis and Isometric Extension Peak Torque.



Solid State Line Represents Line of Best Fit and Surrounding Curved Lines Represent 95% Confidence Intervals.

Figure 6. Relationship Between Vastus Medialis and Vastus Lateralis and Isokinetic Extension Peak Torque.



Solid State Line Represents Line of Best Fit and Surrounding Curved Lines Represent 95% Confidence Intervals.

Spearman-rho correlations of isometric flexion peak torque revealed that ST (r_s=0.66, p<0.001) and BFLH (r_s=0.63, p<0.001) thicknesses were moderately correlated with isometric flexion. Spearman-rho correlations of isokinetic flexion peak torque revealed that ST (r_s=0.65, p<0.001) and BFLH (r_s=0.53, p=0.002) thicknesses were moderately correlated with isokinetic flexion. Scatter plots of flexor correlations are located in figures 7 & 8.

Figure 7. Relationship Between Semitendinosus and Biceps Femoris Long Head and Isometric Flexion Peak Torque.

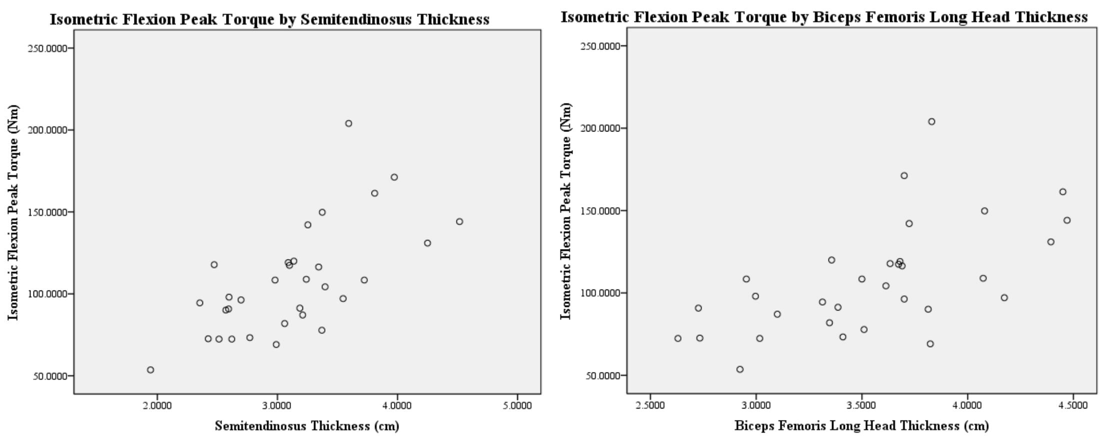
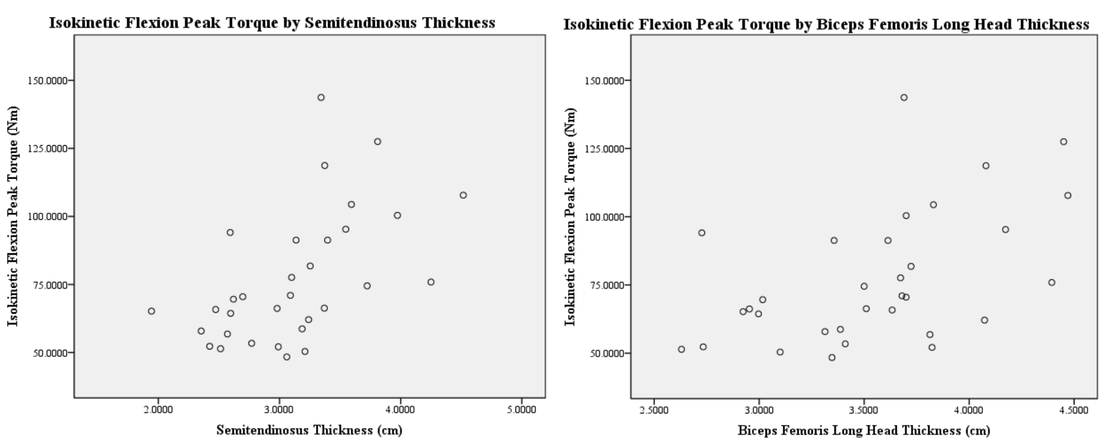


Figure 8. Relationship Between Semitendinosus and Biceps Femoris Long Head and Isokinetic Flexion Peak Torque.



Multi-muscle Models

To better understand which individual quadriceps or hamstrings could be best predictive of isokinetic or isometric extension or flexion strength as well as to determine if a multi-muscle model could better predict strength, stepwise regressions were performed. From the stepwise regression of isometric knee extension peak torque the VL entered initially (R^2=0.31, P = 0.001), whereas the VM did not significantly contribute additional strength variance ($R^2\Delta$= 0.02, PΔ = 0.442). From stepwise regression analysis of isokinetic knee extension peak torque, the VM entered initially (R^2 = 0.29, P = 0.002), whereas the VL did not significantly contribute additional strength variance ($R^2\Delta$= 0.05 PΔ = 0.177).

From the stepwise regression of isometric knee flexion peak torque the ST entered initially (R^2=0.44, P < 0.001), whereas the BFLH did not significantly contribute additional strength variance ($R^2\Delta$ = 0.22, PΔ = 0.242). From stepwise regression analysis of isokinetic knee flexion peak torque, the ST entered initially (R^2 = 0.30, P = 0.001), whereas the BFLH did not significantly contribute additional strength variance ($R^2\Delta$ = 0.18, PΔ = 0.340).

Additional Variables Explored but Not Part of the Thesis Questions

In order to compare muscle thickness measures to common clinical anthropometric measures, stepwise regression was performed in order to explore the potential contributions of thigh girth, and skin fold thickness calculated body fat percentage to knee extension and flexion strength. Demographics of these variables are found in Table 5.

Table 5. Demographic Information

Demographics	n	Thigh Girth (cm)	Body Fat (%)
Total	32	52.9 (3.8)	15.3 (6.9)
Male	15	54.3 (3.6)	10.2 (5.8)
Female	17	51.7 (3.7)	19.8 (3.9)

(Mean (SD)) for Thigh Girth and Skinfold Estimated Body Fat Percentage.

After controlling for gender on the initial step, thigh girth accounted for a relatively low yet significant portion of the variance ($R\Delta^2$=0.232, p=0.001) to isometric extension strength. Body fat percentage did not contribute to prediction of isometric extension strength ($R\Delta^2$=0.008, p=0.482).

Table 6. Stepwise Regression for Effect of Thigh Girth and Body Fat Percentage on Isometric Extension Peak Torque, Controlling for Gender.

Model Summary[d]

					Change Statistics				
Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	R Square Change	F Change	df1	df2	Sig. F Change
1	.573[a]	.329	.306	46.5385036	.329	14.699	1	30	.001
2	.749[b]	.560	.530	38.3071192	.232	15.278	1	29	.001
3	.754[c]	.568	.522	38.6370666	.008	.507	1	28	.482

a. Predictors: (Constant), Gender 0=F

b. Predictors: (Constant), Gender 0=F, T. Girth

c. Predictors: (Constant), Gender 0=F, T. Girth, 1BF%

d. Dependent Variable: isoMextPeakT (Nm)

Table 7. Stepwise Regression for Effect of Thigh Girth and Body Fat Percentage on Isometric Flexion Peak Torque, Controlling for Gender.

Model Summary[d]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	.647[a]	.419	.400	25.7570431	.419	21.646	1	30	.000
2	.727[b]	.528	.495	23.6182012	.109	6.680	1	29	.015
3	.727[c]	.529	.479	24.0038585	.001	.076	1	28	.785

a. Predictors: (Constant), Gender 0=F

b. Predictors: (Constant), Gender 0=F, T. Girth

c. Predictors: (Constant), Gender 0=F, T. Girth, 1BF%

d. Dependent Variable: isoMflexPeakT (Nm)

R Square Change is Individual Variable Contribution to Variance.

After controlling for gender on the initial step, thigh girth accounted for a relatively low yet significant portion of the variance ($R\Delta^2$=0.11, p=0.015) to isometric flexion strength. Body fat percentage did not contribute to prediction of isometric flexion strength ($R\Delta^2$=0.001, p=0.785).

Table 8. Stepwise Regression for Effect of Thigh Girth and Body Fat Percentage on Isokinetic Extension Peak Torque, Controlling for Gender.

Model Summary[d]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	.655[a]	.428	.409	25.9801900	.428	22.482	1	30	.000
2	.782[b]	.612	.585	21.7766390	.183	13.700	1	29	.001
3	.796[c]	.634	.595	21.5237036	.022	1.686	1	28	.205

a. Predictors: (Constant), Gender 0=F

b. Predictors: (Constant), Gender 0=F, T. Girth

c. Predictors: (Constant), Gender 0=F, T. Girth, 1BF%

d. Dependent Variable: isoKextPK TQ (Nm)

R Square Change is Individual Variable Contribution to Variance.

After controlling for gender, thigh girth accounted for a relatively low yet significant portion of the variance (R^2=0.18, p=0.001) to isokinetic extension strength.

Body fat percentage did not contribute to prediction of isokinetic extension strength (R^2=0.02, p=0.205).

Table 9. Stepwise Regression for Effect of Thigh Girth and Body Fat Percentage on Isokinetic Flexion Peak Torque, Controlling for Gender.

Model Summary[d]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	.703[a]	.494	.477	17.4914410	.494	29.281	1	30	.000
2	.758[b]	.574	.545	16.3155967	.080	5.480	1	29	.026
3	.762[c]	.580	.535	16.4901830	.006	.389	1	28	.538

a. Predictors: (Constant), Gender 0=F

b. Predictors: (Constant), Gender 0=F, 1BF%

c. Predictors: (Constant), Gender 0=F, 1BF%, T. Girth

d. Dependent Variable: isoKflexPK TQ (Nm)

R Square Change is Individual Variable Contribution to Variance.

After controlling for gender, body fat percentage accounted for a very low yet significant portion of the variance (R^2=0.08, p=0.026) to isokinetic flexion strength. Thigh girth did not significantly contribute to prediction of isokinetic flexion strength (R^2=0.006, p=0.583).

CHAPTER V

MANUSCRIPT

Introduction

Thigh strength is an essential measure of athletic performance as well as an indicator of recovery from injury and disease. A wide range of clinicians and strength and conditioning experts incorporate thigh-strengthening activities into the daily routine of their patients and clients. Greater thigh strength improves indicators of athletic performance such as squat max, sprint time, pro-agility tests, and time-to-fatigue across various sports, such as rugby, cycling, skiing, strongman, and Nordic Combined (Wang et al., 2016; Rønnestad et al., 2010; Losnegard at al., 2011; Winwood et al., 2012; Rønnestad et al., 2012). Symmetrical isokinetic (dynamic) strength between injured and uninjured quadriceps and hamstrings (injured has 85-90% strength of uninjured) has also been shown to be an indicator of return to play eligibility (Ménétrey et al., 2014). In fact, it has been shown that as it relates to the injury of the thigh, isometric (static) strength of the injured limb proportional to the uninjured limb is a better indicator of return-to-play eligibility than time away from sport (Moen et al., 2014). Collectively this indicates that development and subsequent assessment of thigh strength is a critical component of caring for patients and clients.

Strength can be directly assessed directly and indirectly. Directly, isolated strength of a muscle group can be tested in a lab or clinical setting using instrumented dynamometry. Instrumented dynamometry is the measurement of force produced with hand-held or freestanding instrumentation such as a Biodex Dynamometer (Koutedakis & Sharp, 2004). Likewise, strength of the thigh can be assessed with functional tasks such as single leg hops, countermovement jumps, vertical jumps, and many other methods (Pyne et al., 2006). However, many of these functional thigh strength tests can put the integrity of the tissue at risk when dealing with clinical populations as they may place undo/unsafe loads upon healing /diseased passive stabilizing structures. While there are cases and situations when strength should not be directly assessed during a certain stage of injury/illness care, such as during the early phases of ACL rehabilitation (Feller et al., 2002), there are indirect measures of strength than may prove valuable for such populations.

Body anthropometrics (i.e. size measures of the human body) can provide indirect measures of thigh strength. The traditional clinical anthropometric measure representative of thigh strength is thigh girth (Gross et al., 1989). This measure is designed to estimate the overall size of the thigh muscles. Although clinically efficient, this measure is not a true measure of cross-sectional area of the muscles of the thigh since it ignores fat and bone as parts of the measure (Brozek et al., 1953). Thigh girth has been shown to indirectly estimate strength of the knee extensors and flexors in resistance trained athletes (Mayhew et al., 1993), but this does not seem to apply to all populations, such as those with greater adipose tissue as well as women (Brozek et al., 1953; Hosler et al., 1977). Since skin, fat, and other subcutaneous tissues are included, thigh girth fails to accurately measure thigh muscle cross-sectional area in many cases (Schantz et al., 1981).

Modern imaging techniques such as computed tomography (CT), magnetic resonance imaging (MRI), dual-x-ray absorptiometry (DXA), and ultrasound are all capable of assessing thigh girth, thigh muscle cross-sectional area, and fat content (Dupont et al., 2001; Worsley et al., 2014; Malkov et al., 2015). While all are medically available, ultrasound is likely the most clinically available, cost-effective, and patient-safe imaging modality (Seymour et al., 2009). Ultrasound is able to reasonably match the gold standards of MRI and computed tomography (CT) in measuring the individual cross-sectional areas of quadriceps and hamstring muscles (Worsley et al., 2014; Noorkoiv et al., 2010; Walton et al., 1997; Lima et al., 2012; Ahtiainen et al., 2010). However, many clinical ultrasound machines are incapable of measuring cross-sectional area of thigh muscles due to the field of view being too small relative to the size of the knee extensors and flexors (Abe et al., 2015). In such clinical scenarios, ultrasound-based measures can accurately measure thickness of the knee extensors and knee flexors (Abe et al., 2015, 2016) with muscle thickness measures having been found to indirectly indicate muscle strength and performance (Moreau et al., 2010).

It is still unknown if individual muscle morphology is more directly associated with knee extensor and flexor strength than the common clinical measure of thigh girth. Specially, determining the importance of individual components of quadriceps and hamstrings to their respective strength producing capacity about the knee may refine clinical practice, given studies suggesting muscle specific atrophy or alterations (Marcon et al., 2015a, 2015b; Williams et al., 2005; Timmins et al., 2016). Further, in simple tasks such as knee extension and knee flexion, it is still not known which individual muscles are most closely associated with the strength of their respective groups. Understanding the role of individual muscle size to strength of the respective group as a whole may help clinicians to better understand how muscle atrophy may affect the expression of joint strength. The purpose of this study was to determine the relationships of vastus medialis and vastus lateralis thicknesses to knee extension strength as well as semitendinosus and biceps femoris long head thicknesses to knee flexion strength. It was hypothesized that the vastus medialis, vastus lateralis, semitendinosus, and biceps femoris long head muscle thicknesses would all be individually associated with strength of their respective actions about the knee. It was further hypothesized that the VM would be more closely associated with knee extensor strength than the VL since the vastus medialis is the most affected after reconstructive surgery and rehabilitation (Marcon et al., 2015a, 2015b). It was further hypothesized that the BFLH would be more closely associated with knee flexor strength than the ST since such great architectural changes in the BFLH occur in conjunction with knee flexor strength deficits (Timmins et al., 2016).

Methods

Participants

In total, thirty-two healthy, physically able individuals participated in the study (see Table 1 for demographics). Fifteen males and fifteen females were recruited from a convenience sample from the University of North Carolina at Greensboro. All participants were free from lower extremity knee injury or surgeries and were recreationally active (exercise of resistance or aerobic training at least 3 days per week, 30 minutes per day). All participants provided an informed consent and a basic health history and physical activity questionnaire. All procedures for the study were approved by the University of North Carolina at Greensboro Institutional Review Board.

Instrumentation

Ultrasound measures of muscle thickness were obtained with B-Mode clinical ultrasound (Fujifilm, SonoSite MicroMaxx, Bothell, WA, United States) with a HFL38/13-6 MHz transducer. Knee flexion and extension strength was measured using an instrumented dynamometer (Biodex System 3, Biodex Medical Systems, Shirley, NY, United States).

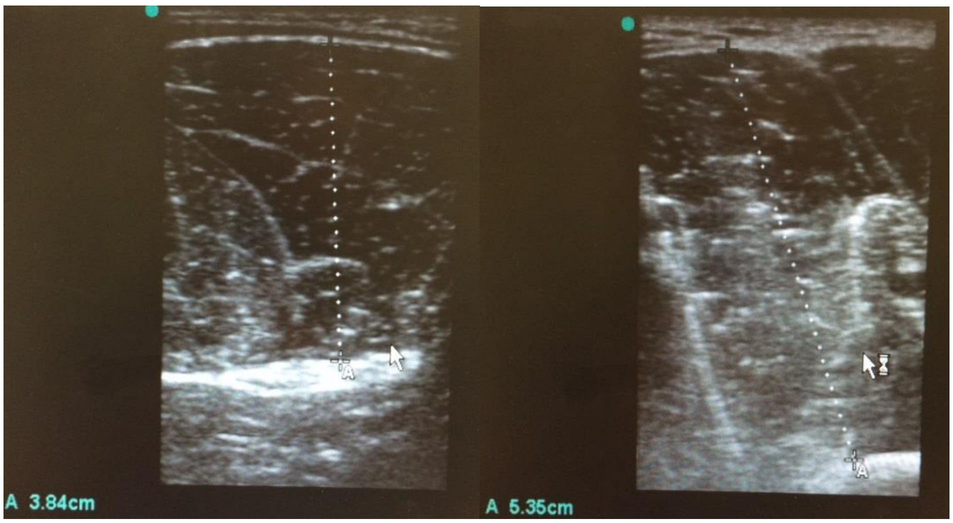
Procedures

Data were gathered over 48 hours of testing. On day one, subjects gave written consent, were familiarized with all procedures, had muscle thickness data gathered, and were familiarized to perform maximal voluntary isometric contractions (MVIC) and isokinetic contractions. On day two, subjects had anthropometrics (height, weight, and muscle thickness (MT)) assessed and performed the MVIC and isokinetic protocols for muscle strength as described below (Schmitz et al., 2000).

Day One

All quadriceps muscle thicknesses were measured along the circumference of the individual muscle bellies at the point 50% the length of the femur between the greater trochanter and lateral condyle of the femur (Abe et al., 2015) while all hamstring muscle thicknesses were measured along the circumference of the individual muscle bellies at the point 60% the length of the femur from the greater trochanter to the lateral condyle of the femur (Abe et al., 2016) and measured using real-time B-mode SonoSite MicroMaxx ultrasound with the HFL38/13-6 MHz transducer. A marker pen was used to mark the greater trochanter and lateral condyle in order to facilitate locating the specific imaging site (Abe et al., 2016). A tape measure was used to provide a transverse line marked with the pen around the thigh at 50% and 60% lengths in order to provide a constant reference during imaging. The specific muscles measured were the vastus medialis, vastus lateralis, semitendinosus, and biceps femoris long head (Abe et al., 2015, 2016).

Figure 9. Measurement Method (position) for Biceps Femoris (left) and Vastus Medialis (right)



For imaging the quadriceps, the participant was seated in a relaxed position in the Biodex System 3 dynamometer and the knee was placed in the same 60° knee flexion as the isometric test so as to make the measurement more accurate to the task (Sogabe et al., 2009; De et al., 2008; Hacker et al., 2016). For imaging the hamstrings, the participant laid face down on the Biodex and had their knee held steady in 45° of flexion (confirmed with a goniometer) to best mimic the positioning of the limb in the isometric task.

Subjects were asked to simply sit quietly and relax in order to make measurements consistent and unaffected by perturbations.

Figure 10. Positioning for Imaging of Quadriceps and Hamstrings, Respectively

The caliper function on the SonoSite MicroMaxx was engaged and the muscle thickness was recorded as the average distance in centimeters of three repeated measures from the superficial border of the muscle belly to the deep border of the muscle belly. This was found by identifying the medial and lateral borders of the individual muscles, finding the halfway point between the two, and measuring from superficial border to deep border of each muscle. The line of sight was drawn to the nearest point of the deep border of each muscle (Moreau et al., 2010; Abe et al., 2014, 2015, 2016; Freilich et al., 1995). See figure 1 for example. This helped control for muscles that do not make contact with the femur at certain lengths. This procedure was repeated on day 1 and day 2 to allow for establishment of intratester between day measurement consistencies.

To serve as a strength assessment familiarization, both isometric and isokinetic strength were tested; with isometric strength measured first and isokinetic second (Shultz et al., 2009) on day 1. Following a 5-minute warm up on a cycle ergometer, knee extension and flexion maximal voluntary isometric contraction (MVIC) torque (Nm) were tested using a Biodex System 3 dynamometer (Biodex Medical Systems Inc.; Shirley, NY). The dominant limb (defined as the stance limb when kicking a ball) of subjects was tested. Knee extension and flexion MVICs were obtained at 60° and 45°, respectively (Murray et al., 1977). The back of the seat was set to 100°. The axis of rotation of the dynamometer was in line with the lateral epicondyle of the femur and the resistance pad will be placed 2 inches above the ankle joint (Shultz et al., 2009). Participants sat with their arms across their chest and verbally encouraged during the procedure to kick or pull for knee extension or flexion, respectively (Shultz et al., 2009). Participants performed three preparation trials at 25%, 50%, and 75% of the perceived maximal contraction; then at 100% for three 5-second MVIC trials with 60 seconds of rest between trials (Montgomery & Shultz, 2010; Kollock et al., 2015). After a 5-minute rest period, isokinetic strength was tested (Schmitz & Westwood, 2001).

Figure 11. Isometric Extension Testing

Isokinetic testing was performed with the subject seated in the dynamometer with the seat set to 100° (Schmitz & Westwood, 2001). Isokinetic knee extensor and flexor torque (Nm) was tested between 0° and 90° of knee flexion with Biodex System 3 dynamometer. The participants performed 5 warm-up repetitions at submaximal and maximal effort and then performed 5 trials of maximal effort at 180°/s, which has been used in studies testing isokinetic strength and has similar results to speeds of 120°/s and 60°/s (Kollock et al., 2015; Tsiokanos et al., 2002; Schmitz & Westwood, 2001).

Day Two

Consistent with the methods for day one, ultrasound measured muscle thickness data were gathered as well as isokinetic and isometric strength data. Due to the need for familiarization on day one, strength data recorded from day two was specifically used for further analysis. When asked, no subjects reported soreness from the prior testing session.

Data Reduction and Analysis

The Biodex System 3 dynamometer was connected to a computer to record torques (Nm) from respective tests. For the MVIC trials, the highest peak value obtained over the 5 sec MVICs was used for analyses. For the knee extension and flexion isokinetic trials the peak torque was measured as the angle-specific torque across trials at 60° and 45° of knee flexion, respectively. Data were then imported into Microsoft Excel for further analysis.

The images used to measure muscle thickness of each muscle were imported into a computer to 2D SiteLink image analysis software in order to record results. Muscle thicknesses of each muscle were recorded for the VM, VL, ST, and BFLH as described above in Microsoft Excel for analysis. The averages of 3 measures for each of the four muscles were included for analyses.

Using muscle thickness data obtained on each day, intratester between day reliability and precision was established examining the $ICC_{2,3}$ and standard error of measurement for each muscle thickness. Next, all data were initially tested for normality using the Shapiro–Wilk test. Pearson correlations with an alpha level of ($P \leq 0.05$) were then run to determine if the VM or VL were able to determine the association with isometric and isokinetic knee extensor strength and if the ST or BFLH were able to determine the association with isometric and isokinetic knee flexor strength. In order to provide a comparison of individual VM, VL, ST, and BFLH, stepwise regression analysis was used to determine what amount of the variance could be accounted for by VM, VL, ST, and BFLH for their respective actions. In the case of non-normally distributed data, Spearman-Rho correlations were completed and followed up with stepwise regressions as described above.

Results

Participant demographics are included in Table 10. Ultrasound measures were all found to be reliable and precise from day one to day two (ST $ICC_{2,3}$ = 0.95±0.2cm; BFLH $ICC_{2,3}$ = 0.93±0.2cm; VMO $ICC_{2,3}$ = 0.92±0.2cm; VL $ICC_{2,3}$ = 0.93±0.2cm). All ICC values were deemed within the "excellent" range for reliability (Cicchetti, 1994).

Table 10. Demographic Information.

Demographics	Total	Male	Female
n	32	15	17
Age (yrs)	21.2 (3.2)	22.4 (3.6)	20 (2.3)
Height (cm)	173.7 (9.6)	179.3 (8.7)	168.8 (7.7)
Mass (kg)	74 (13.7)	80.7 (11.1)	68.2 (13.2)
Stance Limb	L = 28; R = 4	L = 13; R = 2	L = 15; R = 2
ST thickness (cm)	3.1 (0.6)	3.5 (0.5)	2.8 (0.4)
BFLH thickness (cm)	3.5 (0.5)	3.9 (0.4)	3.3 (0.4)
VM thickness (cm)	4.8 (0.5)	5.2 (0.4)	4.5 (0.4)
VL thickness (cm)	5.0 (0.5)	5.4 (0.2)	4.7 (0.5)
Isometric Extension Peak Torque (Nm)	218.2 (55.9)	251.8 (45.3)	188.6 (47.6)
Isometric Flexion Peak Torque (Nm)	107.6 (33.2)	130.1 (32.8)	87.7 (17.4)
Isokinetic Extension Peak Torque (Nm)	130.9 (33.8)	154.1 (29.7)	110.4 (22.2)
Isokinetic Flexion Peak Torque (Nm)	77.1 (24.2)	94.9 (22.6)	61.4 (11.3)

All Values are as “Mean (Standard Deviation)”.

Shapiro-Wilk tests revealed that data were normally distributed with the exception of isometric (P=0.04) and isokinetic flexion (P=0.04) peak torques. Therefore, Spearman-rho correlations were performed in place of Pearson correlations when using these variables.

Master correlation matrices are found in tables 11 and 12.

Table 11. Pearson Correlations

Correlations

		ST2 Avg	BFLH2 Avg	VM2 Avg	VL2 Avg	isoMextPeakT (Nm)	isoMflexPeak T (Nm)	isoKextPK TQ (Nm)	isoKflexPK TQ (Nm)
ST2 Avg	Pearson Correlation	1	.732	.597	.564	.588	.666	.565	.550
	Sig. (2-tailed)		.000	.000	.001	.000	.000	.001	.001
	N	32	32	32	31	32	32	32	32
BFLH2 Avg	Pearson Correlation		1	.659	.660	.508	.597	.583	.504
	Sig. (2-tailed)			.000	.000	.003	.000	.000	.003
	N		32	32	31	32	32	32	32
VM2 Avg	Pearson Correlation			1	.689	.526	.522	.584	.379
	Sig. (2-tailed)				.000	.002	.002	.000	.032
	N			32	31	32	32	32	32
VL2 Avg	Pearson Correlation				1	.553	.400	.525	.387
	Sig. (2-tailed)					.001	.026	.002	.031
	N				31	31	31	31	31
isoMextPeakT (Nm)	Pearson Correlation					1	.758	.764	.587
	Sig. (2-tailed)						.000	.000	.000
	N					32	32	32	32
isoMflexPeakT (Nm)	Pearson Correlation						1	.643	.683
	Sig. (2-tailed)							.000	.000
	N						32	32	32
isoKextPK TQ (Nm)	Pearson Correlation							1	.735
	Sig. (2-tailed)								.000
	N							32	32
isoKflexPK TQ (Nm)	Pearson Correlation								1
	N								32

ST2avg = Semitendinosus Thickness, BFLH2avg = Biceps Femoris Long Head Thickness, VM2avg = Vastus Medialis Thickness, VL2avg = Vastus Lateralis Thickness, isoMextPeakT = Isometric Extension Peak Torque, isoMflexPeakT = Isometric Flexion Peak Torque, isoKextPKTQ = Isokinetic Extension Peak Torque, isoKflexPKTQ = Isokinetic Flexion Peak Torque

Table 12. Spearman-Rho Correlations for Nonparametric Statistics

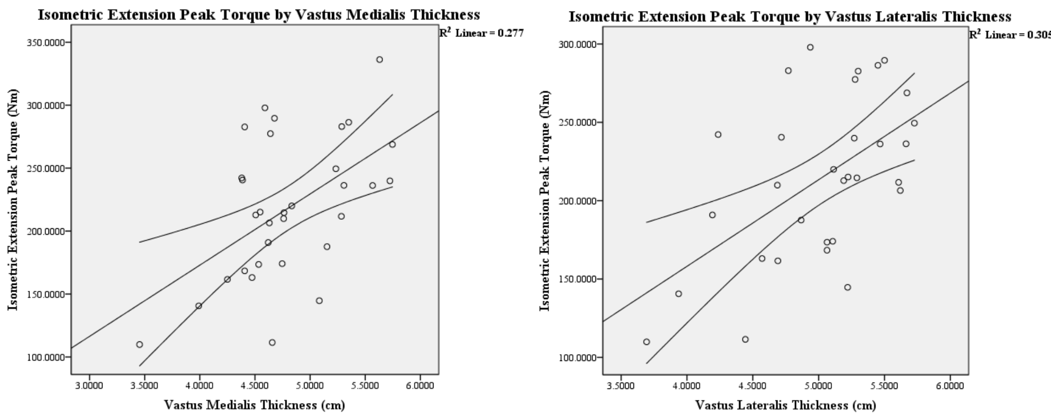
Correlations

			ST2 Avg	BFLH2 Avg	VM2 Avg	VL2 Avg	isoMextPeakT (Nm)	isoMflexPeak T (Nm)	isoKextPK TQ (Nm)	isoKflexPK TQ (Nm)
Spearman's rho	ST2 Avg	Correlation Coefficient	1.000	.696	.573	.546	.529	.664	.577	.646
		Sig. (2-tailed)	.	.000	.001	.001	.002	.000	.001	.000
		N	32	32	32	31	32	32	32	32
	BFLH2 Avg	Correlation Coefficient		1.000	.677	.589	.500	.628	.537	.529
		Sig. (2-tailed)		.	.000	.000	.004	.000	.002	.002
		N		32	32	31	32	32	32	32
	VM2 Avg	Correlation Coefficient			1.000	.633	.440	.501	.514	.515
		Sig. (2-tailed)			.	.000	.012	.004	.003	.003
		N			32	31	32	32	32	32
	VL2 Avg	Correlation Coefficient				1.000	.519	.522	.541	.519
		Sig. (2-tailed)				.	.003	.003	.002	.003
		N				31	31	31	31	31
	isoMextPeakT (Nm)	Correlation Coefficient					1.000	.843	.806	.625
		Sig. (2-tailed)					.	.000	.000	.000
		N					32	32	32	32
	isoMflexPeakT (Nm)	Correlation Coefficient						1.000	.786	.751
		Sig. (2-tailed)						.	.000	.000
		N						32	32	32
	isoKextPK TQ (Nm)	Correlation Coefficient							1.000	.805
		Sig. (2-tailed)							.	.000
		N							32	32
	isoKflexPK TQ (Nm)	Correlation Coefficient								1.000
		Sig. (2-tailed)								.
		N								32

ST2avg = Semitendinosus Thickness, BFLH2avg = Biceps Femoris Long Head Thickness, VM2avg = Vastus Medialis Thickness, VL2avg = Vastus Lateralis Thickness, isoMextPeakT = Isometric Extension Peak Torque, isoMflexPeakT = Isometric Flexion Peak Torque, isoKextPKTQ = Isokinetic Extension Peak Torque, isoKflexPKTQ = Isokinetic Flexion Peak Torque

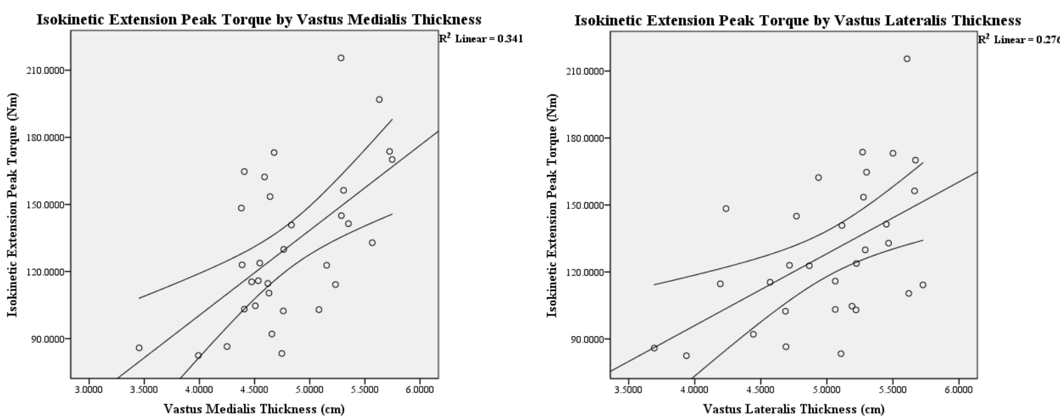
Pearson correlations of isometric extension peak torque revealed that VM ($r=0.53$, $p=0.002$) and VL ($r=0.55$, $p=0.001$) thicknesses were moderately correlated with isometric extension. Pearson correlations of isokinetic extension peak torque revealed that VM ($r=0.58$, $p<0.001$) and VL ($r=0.52$, $p=0.002$) thicknesses were moderately correlated with isokinetic extension. Scatter plots of extensor correlations are located in figures 12 & 13.

Figure 12. Relationship Between Vastus Medialis and Vastus Lateralis and Isometric Extension Peak Torque.



Solid State Line Represents Line of Best Fit and Surrounding Curved Lines Represent 95% Confidence Intervals.

Figure 13. Relationship Between Vastus Medialis and Vastus Lateralis and Isokinetic Extension Peak Torque.



Solid State Line Represents Line of Best Fit and Surrounding Curved Lines Represent 95% Confidence Intervals.

Spearman-rho correlations of isometric flexion peak torque revealed that ST (r_s=0.66, $p<0.001$) and BFLH (r_s=0.63, $p<0.001$) thicknesses were moderately correlated with isometric flexion. Spearman-rho correlations of isokinetic flexion peak torque revealed that ST (r_s=0.65, p<0.001) and BFLH (r_s=0.53, p=0.002) thicknesses were moderately correlated with isokinetic flexion. Scatter plots of flexor correlations are located in figures 14 & 15.

Figure 14. Relationship Between Semitendinosus and Biceps Femoris Long Head and Isometric Flexion Peak Torque.

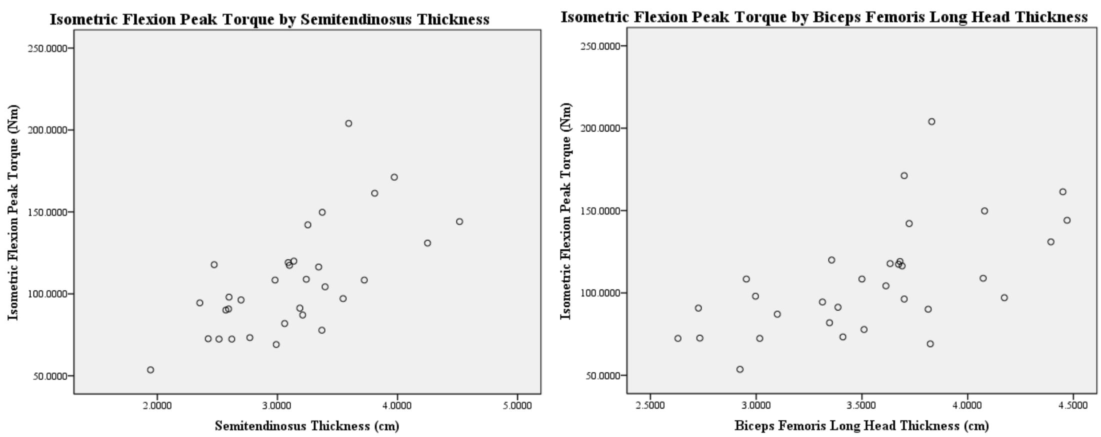
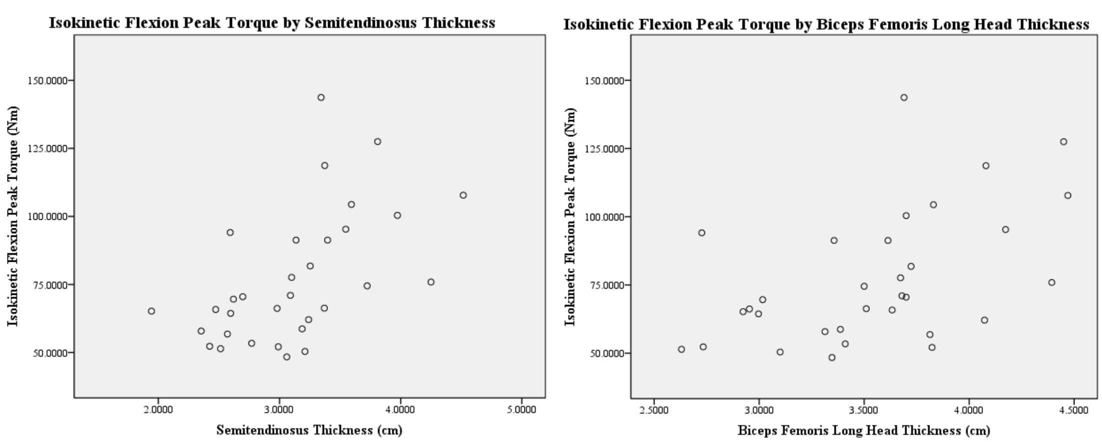


Figure 15. Relationship Between Semitendinosus and Biceps Femoris Long Head and Isokinetic Flexion Peak Torque.



Multi-muscle Models

To better understand which individual quadriceps or hamstrings could be best predictive of isokinetic or isometric extension or flexion strength as well as to determine if a multi-muscle model could better predict strength, stepwise regressions were performed. From the stepwise regression of isometric knee extension peak torque the VL entered initially (R^2=0.31, P = 0.001), whereas the VM did not significantly contribute additional strength variance ($R^2\Delta$= 0.02, $P\Delta$ = 0.442). From stepwise regression analysis of isokinetic knee extension peak torque, the VM entered initially (R^2 = 0.29, P = 0.002), whereas the VL did not significantly contribute additional strength variance ($R^2\Delta$= 0.05 $P\Delta$ = 0.177).

From the stepwise regression of isometric knee flexion peak torque the ST entered initially (R^2=0.44, P < 0.001), whereas the BFLH did not significantly contribute additional strength variance ($R^2\Delta$ = 0.22, $P\Delta$ = 0.242). From stepwise regression analysis of isokinetic knee flexion peak torque, the ST entered initially (R^2 = 0.30, P = 0.001), whereas the BFLH did not significantly contribute additional strength variance ($R^2\Delta$ = 0.18, $P\Delta$ = 0.340).

Discussion

This study investigated the associations between individual muscle thicknesses in the thigh and their respective strength as measured about the knee. All muscle thicknesses were individually moderately associated with their respective action strength. Multi-muscle models were not more strongly correlated with strength than using a single muscle thickness. The discussion here will focus on the interpretation and clinical utility of current findings.

VM, VL, ST, BFLH muscle thicknesses were all individually moderately correlated ($r = 0.53$-0.66) to strength of their respective actions about the knee. This left a relatively large amount of the variance in strength unexplained. Some of this unexplained variance could be partially accounted for by muscle quality. One measure of muscle quality is muscle density, which is defined as the mass of the muscle divided by its volume, which is negatively influenced by intramuscular fatty infiltration (Looijaard et al., 2016; Fukimoto et al., 2012). One study determined the association of quadriceps muscle density (as measured by echo intensity ultrasound) with quadriceps muscle thickness to assess knee extension strength. Separately, quadriceps muscle thickness was correlated with knee extension strength ($r = 0.47$, $p < 0.01$) and echo intensity measured quadriceps muscle density was also correlated with knee extension strength ($r = 0.40$, $p < 0.01$). When both quadriceps thickness and quadriceps muscle density were used to predict knee extension strength with stepwise regression, both entered significantly and the combination was correlated ($r = 0.54$, $p < 0.01$) (Fukimoto et al., 2012). Although the current study did not assess density, it may be important as a direct anthropometric measure in addition to muscle thickness (Hogrel et al., 2015; Malkov et al., 2015; Looijaard et al., 2016).

Neural adaptation is another measure of muscle quality that is defined as the increased ability of neurons to activate motor units within skeletal muscle (Sale, 1988). A common method to measure neural adaptations to exercise is by measuring the central activation ratio (CAR), which measures how many motor units are being voluntarily recruited as well as the volitional firing rate of those motor units (Pietrosimone & Ingersoll, 2009). It is understood that those who undergo resistance training increase the neural drive to muscle (Sale, 1988) and therefore it is likely that given the range of participant activity levels in the current study that resistance-trained subjects may have had some neural adaptations that cardiovascular trained subjects did not. The association between quadriceps muscle quality as measured by CAR, quadriceps CSA, and knee extension strength determined that quadriceps CAR was correlated with knee extension strength ($r = 0.61$, $p = 0.001$) and quadriceps CSA was also correlated with knee extension strength ($r = 0.50$, $p = 0.013$) (Scott et al., 2007). When the two variables were combined to predict knee extension strength, more of the variance was accounted for ($r = 0.63$, $p = 0.001$), but not much more than was accounted for by CAR alone (Scott et al., 2007). Collectively, these studies suggest that thigh muscle neural drive account for additional variance in strength which we could not account for in this study.

Current results compare favorably with prior work that has investigated the relationships of muscle groups rather than individual muscles to knee extension strength (Maughan et al., 1983, 1984b). Maughan et al reported that both males ($r = 0.59$, $p < 0.01$) and females ($r = 0.51$, $p < 0.01$) had significant correlations between quadriceps CSA and knee extension strength (Maughan et al., 1983). Since the current study found similar magnitude correlations of strength and individual muscle thickness, this suggests that thigh muscle thickness may be a comparable correlate of whole muscle group CSA when predicting strength about the knee. This would make further studies of quadriceps and hamstrings morphology easier to produce because ultrasound, which is relatively inexpensive and easy to use, can be utilized with a simple standard measure of muscle thickness, rather than a CT or MRI, which can be expensive and require more training.

The magnitudes of correlations between all muscles and measures of strength were very similar. This suggests that individual muscles contribute similarly to different measures of strength in their respective actions, which is expected as the individual quadriceps and the individual hamstrings are performing the same respective actions at the knee. This can be interpreted as measures of individual thigh muscle thicknesses will account for roughly the same variance for either isokinetic or isometric strength.

Activity and strength levels of participants in the current investigation may have also influenced magnitude of the individual relationships of thickness to strength. Participants were recreationally active in an array of activities, with some doing mostly aerobic training and others primarily engaged in resistance training. In addition, subjects reported a wide range in training frequency. While subjects were purposely chosen across a wide range of activities to ensure a wide and even distribution of the data, training status has been shown to have an effect on several factors in force production and this likely accounted for additional variance (Maughan et al., 1984b). Factors in training status include what kind of training participants regularly engage in as well as how often they engage in their training. Our sample included those that were resistance trained, those who were cardiovascular trained, those who did both, and all of these at different frequencies. As discussed above, those who are resistance trained make specific neural adaptations that alter their muscle quality and these varieties of training likely resulted in varieties in muscle quality, particularly in neural adaptations (Sale, 1988).

With regard to the multi-muscle models explaining knee flexor and knee extensor strength, the addition of a second muscle did not significantly add to the ability to predict strength. As discussed above, both the medial and lateral quadriceps and hamstrings had very similar correlations to their respective strength values (Tables 2 and 3). Because a second muscle did not significantly add to any regression model ($R^2\Delta$ range = 0.02 – 0.22, all $p > 0.05$) it appears as though they explain similar portions of variance in strength. This finding is supported by other research using a single thickness measure to assess thigh muscle size as well as studies that use a single quadriceps CSA as a correlate with strength. Maughan et al used CT to measure the CSA of the quadriceps as a whole, and reported similar correlations of CSA to strength ($r = 0.51$-0.59, $p < 0.01$) (Maughan 1983, 1984b) when compared to the current study. Similarly, Freilich et al used ultrasound to measure quadriceps thickness from the lateral fascia latae to the femur (Freilich et al., 1995) and correlated this measure with quadriceps strength ($r = 0.71$, $p < 0.001$) finding, again, similar values to the current investigation. Lastly, Moreau et al looked at quadriceps thickness with ultrasound by assessing vastus lateralis thickness and reported strong correlations with knee extension strength ($r = 0.92$, $p < 0.05$) (Moreau et al., 2010), which corroborates with our data, although the relationship in Moreau et al is much stronger than ours, likely due to a small sample size ($n = 18$) and the fact that all of their participants were untrained boys around age 12, making their sample much more homogenous than the current investigation. This collectively suggests that in a clinical setting those individual muscle thicknesses of the thigh, either the medial or lateral, may be used to indirectly represent strength. While the majority of this work has been done in a healthy, uninjured population, these relationships need to be established in individuals suffering atrophy as the result of disease or injury.

The study is limited in several manners. The ultrasound device used in the current investigation had a maximum of 6cm depth of view. This made it impossible to measure muscle thicknesses in larger participants. This required us to turn away fifteen potential subjects with larger thigh size. It is possible that this resulted is a lesser distribution of muscle thickness values which may have limited our ability to fully predict strength. Future studies should utilize ultrasound with greater field of view in order to recruit a wider array of participants. As described above, muscle quality was not able to be measured and this could have serious implications for the association between strength and thickness. A qualitative assessment of the ultrasound images makes it clear that there are differences in muscle quality between individuals. Future studies should attempt to account for muscle quality. Further, since no subjects had prior knee injury, it is difficult to determine if athletes with prior injuries would have less association between muscle thickness and strength. Future studies should look to compare injured and uninjured limbs between and within subjects in order to better determine this association. Lastly, data in this study was not compared to indirect anthropometric measures such as height, weight, thigh girth, and body fat percentage, which are currently common clinical measures. Further studies should seek to incorporate these measures in order to determine if a stronger association with knee strength could be found.

Summary

In conclusion, this study demonstrates that thigh muscles are individually as predictive of muscle strength as muscle groups taken as a whole. This suggests that either the medial or lateral muscle of the thigh extensors and flexors can be used as an indirect measure of strength about the knee. This has particular clinical application for clinicians attempting to measure strength when direct assessment is not safe. However, further studies will be needed to assess the contribution of muscle quality using ultrasound in order to account for further variance.

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